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of

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**FORWARD ERROR CORRECTION SCHEME FOR DATA
CHANNELS USING UNIVERSAL TURBO CODES**

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CLAIM FOR PRIORITY

This application claims priority under 35 U.S.C. § 1.119(e) of the filing dates of U.S. Provisional Application Nos. 60/072,368, filed January 23, 1998, 60/074,932, filed February 17, 1998, 60/075,742, filed February 23, 1998, and 60/076,464, filed March 2, 1998.

BACKGROUND OF THE INVENTION

The present invention relates to error correction in data communications, and more particularly, to forward error correction (FEC). Even more particularly, the present invention relates the selection and use of optimal Turbo Codes in high performance data communication systems, such as emerging third generation terrestrial cellular mobile radio and satellite telephone systems, for which flexibility in supporting a wide range of system requirements with respect to transmission data rates, channel coding rates, quality of service measures (e.g., latency, bit-error rate, frame error rate), and implementation complexity are highly desirable.

Forward error correction (FEC) is required in terrestrial and satellite radio systems to provide high quality communication over the RF propagation channel, which induces signal waveform and spectrum distortions, including signal attenuation (freespace propagation loss) and multi-path induced fading. These impairments drive the design of the radio transmission and receiver equipment, the design objective of which is to select modulation formats, error control schemes, demodulation and decoding techniques and hardware components that together provide an efficient balance between system performance and implementation complexity. Differences

in propagation channel characteristics, such as between terrestrial and satellite communication channels, naturally result in significantly different system designs. Likewise, existing communication systems continue to evolve in order to satisfy increased system requirements for new higher rate or higher fidelity communication services.

In the case of terrestrial cellular mobile radio telephony, Analog Mobile Phone System (AMPS) is an exemplary first generation system; the U.S. IS-136 and European GSM time-division multiple-access (TDMA) standards and the U.S. IS-95 code-division multiple-access (CDMA) standard are second generation systems; and the wideband CDMA standards currently under development (e.g., CDMA 2000 in the U.S. and UTRA in Europe) are third generation systems.

In the third generation systems the development of flexible, high-speed data communication services is of particular interest. Desirable features include the ability to perform rate adaptation and to satisfy a multiplicity of quality-of-service (QoS) requirements.

Traditional forward error correction (FEC) schemes for communication systems include use of convolutional codes, block codes such as Reed-Solomon or BCH codes, and/or concatenated coding schemes.

Turbo Codes are a relatively new class of block codes that have been demonstrated to yield bit error rate (BER) performance close to theoretical limits on important classes of idealized channels by means of an iterative soft-decision decoding method.

A Turbo encoder consists of a parallel concatenation of typically two systematic, recursive convolutional codes ("constituent codes") separated by an interleaver that randomizes the order of presentation of information bits to the second constituent encoder with respect to the first constituent encoder. The performance of a Turbo Code depends on the choice of constituent codes, interleaver, information block size

(which generally increase with higher data rates), and number of decoder iterations. For a particular Turbo Code, in which the constituent codes are fixed, one can ideally adjust the block size and number of decoder

5 iterations to trade-off performance, latency, and implementation complexity requirements. As the block size changes, however, a new interleaver matched to that block size is required.

In a CDMA network with synchronized base
10 stations, the forward link channels (from base station to user terminal) can be designed to be orthogonal, using, for example, Walsh-Hadamard spreading sequences. This is generally not possible, however, for reverse link channels (from user terminal to base station), which
15 therefore operate asynchronously using spreading sequences that are only quasi-orthogonal. Thus, the reverse links in a synchronous CDMA network typically experience more interference and therefore may require stronger FEC (via lower rate codes) than the forward link
20 channels do.

In an asynchronous CDMA network, the forward and reverse link channels are more similar in terms of interference levels, so it is possible to use a common FEC scheme (or at least more similar FEC schemes) on the
25 two links.

The flexibility and high performance of Turbo Codes make them a potentially attractive technology for sophisticated data communications services. It is therefore desirable to identify Turbo Codes and Turbo
30 coding FEC schemes that best match diverse service requirements with respect to data rates and coding rates while minimizing implementation complexity.

The present invention advantageously addresses the above and other needs by providing methods for
35 designing and using universally optimized Turbo Codes.

SUMMARY OF THE INVENTION

The present invention advantageously addresses the needs above as well as other needs by providing an approach for designing universal constituent codes of
5   Turbo Codes providing optimal performance in conjunction with a variety of different interleaver depths and Turbo Code rates.

The present invention is characterized, in its most basic form as a method of providing forward error
10 correction for data services using a parallel concatenated convolutional code (PCCC) which is a Turbo Code comprising of a plurality of eight-state constituent encoders wherein a plurality of data block sizes are used in conjunction with said Turbo Code.

15 In one variation, the method of forward error correction further uses a universal Turbo Code in a cellular mobile radio system.

In one embodiment, the method of forward error correction further uses a universal Turbo Code in a
20 forward link and a reverse link of a cellular mobile radio system.

Specific universal Turbo Codes, with sets of optimized puncturing patterns capable of providing several commonly used code rates, are identified that
25 provide uniformly near-optimal bit error rate and frame error rate performance over a wide range of information block sizes (hence, data rates) for a set of supported code rates.

Several universal Turbo Codes are identified
30 herein and differ from each other in terms of: 1) the targeted code rate for which the choice of constituent encoders is optimized; and 2) flexibility with regard to the lowest code rate supported.

A suite of preferred universal Turbo Codes is
35 provided from which a Turbo Coding FEC scheme is crafted to best meet the specific design requirements of a sophisticated data communication system.

BRIEF DESCRIPTION OF THE DRAWINGS

The above and other aspects, features and advantages of the present invention will be more apparent from the following more particular description thereof, presented in conjunction with the following drawings wherein:

Figure 1 is a diagram of a CDMA digital cellular mobile radio system hardware;

Figure 2 is a diagram of a CDMA digital cellular mobile radio system hardware which can implement an embodiment of the present invention;

Figure 3 is a functional block diagram of a Turbo Code encoder modified for use with the present invention;

Figure 4 is a functional block diagram of a Turbo Code decoder;

Figures 5, 6, 7, 8 illustrate the Bit Error Rate (BER) performance against signal-to-noise ratio (SNR) for Turbo Code rate 1/2 and rate 1/3 at Interleaver sizes 1000, 512, and 1024 bits when the Turbo Codes use a candidate constituent code represented by d(D), and n(D);

Figure 9 illustrates the puncturing schemes studied for optimizing the rate 1/4 Turbo Codes;

Figures 10, 11, 12 illustrate the BER/FER performance of Constituent Codes #1-3 at a frame size of 512 bits;

Figure 13 illustrates the BER/FER performance of Constituent Code #1, wherein Constituent Code #1 is at a frame size of 1024 bits, and with consistent results found at sizes 2048 and 3072 bits, respectively;

Figure 14 illustrates the BER/FER performance of selected rate 1/4 Turbo Codes at frame size 512 bits, with consistent results found at sizes 1024, 2048, and 3072 bits, respectively;

Figure 15 is a comparison of preferred Turbo Code B against other puncturing schemes at frame size 512 bits;

Figure 16 is a lay-out of candidate puncturing patterns for Turbo Codes of rate 1/3 and rate 1/2 when the constituent codes have rate 1/3;

Figure 17 illustrates a comparison of rate 1/3 puncturing schemes at frame size 512 bits;

Figure 18 illustrates rate 1/2 puncturing schemes at frame size 512 bits, with consistent results found at 1024, 2048, and 3072 bits, respectively;

Figure 19 illustrates a block diagram of a preferred universal constituent encoder for Turbo Codes optimized at code rate 1/2 and rate 1/3 of varying Interleaver depths;

Figure 20 is a functional block diagram for rate 1/4 Turbo Codes optimized at code rate 1/2 and rate 1/3, including interleaving and puncturing, (rate 1/3, and rate 1/2 use analogous processing);

Figure 21 illustrates puncturing patterns for rate 3/8 Turbo Codes;

Figure 22 illustrates rate 3/8 Turbo Codes optimized at code rate 1/2 and rate 1/3 at frame size 512 bits, wherein results are consistent at 1024, 2048, and 3072 bits, respectively;

Figure 23 illustrates puncturing patterns for rate 4/9 Turbo Codes;

Figure 24 illustrates rate 4/9 Turbo Codes optimized at code rate 1/2 and rate 1/3 using frame size 512 bits;

Figure 25 is a functional block diagram of a preferred constituent encoder for Turbo Codes optimized at code rate 1/4;

Figure 26 illustrates a functional block diagram of a rate 1/4 Turbo Codes optimized at rate 1/4 including interleaving and puncturing, (rate 1/3 and rate 1/2 use analogous processing);

Figure 27 illustrates puncturing patterns for rate 2/9 Turbo Codes;

Figure 28 illustrates rate 2/9 Turbo Codes optimized at code rate 1/4 using frame size 512 bits;

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Figure 29 illustrates initial puncturing patterns for rate 3/8 Turbo Codes;

Figure 30 illustrates rate 3/8 Turbo Codes optimized at code rate 1/4 using frame size 512 bits;

Figure 31 is a functional block diagram of a preferred universal constituent encoder for rate 1/2 and rate 1/3 Turbo Codes of varying Interleaver depths; and

Figure 32 illustrates a performance comparison of rate 1/4 FER-optimized Turbo Codes with convolutional codes, at frame size 512 bits, wherein results are consistent at 1024, 2048, and 3072 bits.

Appendix A is a compilation of figures, collectively referred to herein as `analogous' figures, curves or simulations or the equivalent.

Corresponding reference characters indicate corresponding components through out several views of the drawings.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

The following description of the presently contemplated best mode of the invention is not to be taken in a limiting sense, but is made merely for the purpose of describing the general principles of the invention. The scope of the invention should be determined with reference to the claims.

There are at least two primary aspects of the current invention: 1) forward error correction schemes for data services based on specific `universal' Turbo Codes demonstrated to provide near optimal performance over a wide range of information block sizes and code rates; and 2) the method by which specific Turbo Codes having the above mentioned desirable properties can be designed.

Turbo Codes are particularly well-suited to data applications because of their excellent error correction capabilities at low signal-to-noise (SNR) ratios and their flexibility in trading off BER and frame error rate (FER) performance for processing delay. The data

services under consideration in the hereinafter-described embodiments are consistent with third generation Code Division Multiple Access (CDMA) cellular mobile radio standards currently in development and are typically more

5 delay-tolerant than low-rate voice services.

The universal Turbo Codes specified herein (and the method of finding such codes), however, are also applicable to data services in other cellular mobile radio systems (e.g., the European Time-Division Multiple

10 Access (TDMA) standard used in GSM) as well as other communications systems, such as satellite or other wireless communications systems. Several specific Turbo Codes are therefore identified that provide different optimizations regarding these requirements. Others would also be

15 possible.

In order to optimize the performance of Turbo Codes for data services, it is desirable to have a set of "universal" constituent codes that provide optimal or nearly optimal performance in conjunction with a variety

20 of different Interleaver depths and Turbo Code rates, thus avoiding tailoring each optimization of particular Turbo Codes.

Referring first to Figure 1, an exemplary conventional digital cellular mobile radio system using

25 Direct Sequence Code Division Multiple Access (CDMA) Mobile-station-to-base-station (or reverse) link is shown using a convolutional encoder and a Viterbi decoder. This basic coding and interleaving can be applied, equally well, to other multiple access systems such as

30 the Time Division Multiple Access (TDMA) used in a well-known GSM standard.

Figure 1 also represents a base-station-to-mobile-station (or forward) link in a cellular mobile radio system. At a transmitting system 100, the system

35 comprises a segmentation processor 104 where user information bits from a data terminal equipment (not shown) are assembled into fixed length frames of N bits per frame 106 which are input to a convolutional encoder

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108, (of rate r). Convolutional encoder 108 is coupled to the synchronization and framing processor 104 which produces N/r code symbols 110 at an input of a Channel Interleaver 112 coupled to the convolutional encoder 108.

5   The channel interleaver 112, performs pseudo-random shuffling of code symbols 110, and outputs the symbols to a Spread Spectrum modulator 114 coupled to the channel interleaver 112.   The Spread Spectrum modulator 114 uses a user specific Transmit PN-code generated by a PN

10   converter 116 coupled to the Spread Spectrum modulator 114, to produce a spread spectrum signal carried on a RF carrier to a mobile RF transmitter 118.   Mobile RF transmitter 118 is also coupled to the Spread Spectrum modulator 114, where a high power amplifier (not shown)

15   coupled to a transmit antenna 120 radiates a signal to a base station.   The techniques of spread spectrum modulation and RF transmission are well known art to one familiar with spread spectrum communication systems.

A signal from a mobile station (`mobile

20   signal') received at a base station Receive antenna 122 is amplified in a Base RF receiver 124 and demodulated in a Spread Spectrum Demodulator 128, using the same PN-code used by the mobile RF transmitter 118, to de-spread the signal.   The demodulated symbols are de-interleaved by a

25   Channel De-Interleaver 130 and input to a Viterbi decoder 132.   The decoded information bits are reconstructed into receive data blocks 136 and forwarded to the data terminal equipment at the receive end of the system.

Referring next to Figure 2, a hardware system

30   for a digital cellular mobile radio system is shown which implements an embodiment of the present invention.   As before, a reverse link is illustrated although the same block diagram also represents a forward link.   Further, while the CDMA system is used as an example, one familiar

35   with the art would consider the present invention applicable to other systems such as TDMA as well.

Transmit data Blocks 202 from data terminal equipment are segmented and framed at a Segmentation

Processor 204 into fixed frame lengths and applied to a
Turbo Code encoder 208. The output from the encoder 208
is fed to a Channel Interleaver 212 to pseudo-randomize
the code symbols. The Channel Interleaver 212 provides
5   output to a Spread Spectrum Modulator 214 which uses a
user specific PN-code from a PN Generator 216 to create a
spread spectrum signal, carried on a RF carrier to a
mobile RF transmitter 218. The channel interleaver 212
is distinguished from a turbo code interleaver (not
10   shown), which is a component of the encoder 208. The
mobile RF Transmitter 218 coupled to a Transmit Antenna
220 uses a high power amplifier (not shown) at the
Transmit Antenna 220 to radiate the signal to the base
station.

15   A signal from the mobile station received at a
base receive antenna is amplified in a base RF receiver
224 and demodulated in a Spread Spectrum Demodulator 228,
which uses the same PN-code as used by the mobile RF
transmitter 218, to de-spread the signal. The
20   demodulated symbols are de-interleaved by the Channel DE-
Interleaver 230, and input to the Turbo Code decoder 232.
Decoded information bits from the Turbo Code decoder 232
are reconstructed at a Reconstruction Processor 238 into
receive data blocks 236 and forwarded to the data
25   terminal equipment at the receive end.

          Referring to Figure 3, the basic structure of a
Turbo Code is characterized by the parallel concatenation
of two simpler constituent codes at encoder #1 306 and
encoder #2 308. Both constituent encoders, i.e., encoder
30   #1 306 and encoder #2 308 process the same information
bit stream 302, but the encoder #2 308 processes
information bits 302 in a different order than the order
in which encoder #1 306 processes the information bits
302, since the Interleaver 304 reorders the information
35   bits in a pseudo-random manner before they reach encoder
#2 308 (the constituent encoder 308). This arrangement
reduces the likelihood that a sequence of information
bits 302 causing encoder #1 306 to produce a low-Hamming

weight output 310 would also cause encoder #2 308 to do the same with its output 314, which makes possible the excellent performance of Turbo Codes.

Both encoders 306, 308 produce, in addition to the information bits 302 (also referred to as systematic bits 302), parity bits 310, 314 which are punctured by puncturer 312 to achieve a desired overall Turbo Code rate. It is also possible to puncture systematic bits.

The constituent codes of a Turbo Code are usually systematic, recursive convolutional codes. The simplest and most widely known recursive convolutional codes have rate 1/2 and transfer function:

$$G(D) = [1, n(D)/d(D)],$$

where n(D) and d(D) are binary polynomials specifying the feed forward and feedback connections of the encoder, respectively.

The rate of a Turbo Code is changed by changing the selection of output bits 310, 314 for puncturing or transmitting. In all the cases herein, a "1" indicates transmitting; a "0" indicates puncturing.

Figure 3 also shows how two possible puncturing patterns result from puncturer 312. Alternately puncturing the parity bits between encoder 306 and 308 result in a Turbo Code rate r=1/2. Transmitting all of the parity bits at the two encoders 306, 308 produces a code rate r=1/3.

It is not possible to achieve Turbo Code rates lower than 1/3 without either increasing the number of constituent encoders or increasing the number of output parity bits per constituent encoder. The latter is usually preferred in order to reduce implementation complexity. In this case, one considers a rate 1/3 systematic, recursive convolutional code with transfer function:

$$G(D) = [1, n_1(D)/d(D), n_2(D)/d(D)]$$

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Using two such constituent codes provides any Turbo Code rate between 1/5 and 1 through puncturing, or deleting.

Turbo Codes are decoded using iterative
5   decoding methods, as shown in the block diagram of Figure 4.

Each of the constituent codes are decoded separately using likelihood estimates of the other constituent decoder 406 or 416 as `a priori' information.
10   The constituent decoder 406, 416 must be of a soft-input/soft-output type, such as the Maximum A Posteriori (MAP) algorithm, the sub-optimal Soft-Output Viterbi Algorithm (SOVA), or variations. After both constituent decoders have processed the data, the process can be
15   repeated.

In practice, the turbo decoders 406, 416 are usually limited to a fixed number of iterations consistent with the implementation complexity and performance objectives of the system.
20   Figure 4 is a general block diagram of a turbo decoder. Soft information regarding the information bits 404, parity bits for the first encoder 402, and parity bits of the second encoder 402' are received from the demodulator. First, a first decoder 406 uses received
25   information bits 404 and received parity bits 402 to produce a soft decision 408 on information bits. The soft decision 408 is interleaved by an interleaver 412, the output of which is soft decision 414. Soft decision 414 is fed to a second decoder 416 as a priori
30   information.

The second decoder 416 accepts the soft decision 414 described above and produces an improved soft decision 420 on information bits which are then interleaved by an interleaver 422 and fed to the first
35   decoder 406 as a priori information. The whole process is repeated as many times as desired. Final output 420 is obtained by making hard decisions or the soft decisions out of the first or second decoder.

In accordance with the present invention, a single mother Turbo Code and various puncturing patterns are sought to derive uniformly good codes for various code rates and information block sizes.

A methodology for determining universal constituent codes is developed by first limiting the initial pool of possible universal constituent codes in accordance with trade-off studies between performance and implementation complexity. In accordance with the present invention, performance studies using different state codes have shown that eight-state constituent codes provide a good performance trade-off.

Universal constituent codes are first optimized according to the primary code rate of the targeted application. For example, in the case of CDMA data communications, separate optimizations can be done for the forward and reverse links since the reverse links usually require lower code rates for higher coding gain.

The following steps, more fully described below, are used to produce Turbo Codes optimized for rate 1/2 and rate 1/3:

1) select candidate systematic rate 1/2 constituent encoders with transfer function of the form $[1, n(D)/d(d)]$, where $d(D)$ is a primitive polynomial and $n(D)$ starts with 1 and ends with D^3;

2) determine a Turbo Code rate 1/2 and rate 1/3 test puncturing pattern to apply to output data encoded by two rate 1/2 constituent encoders;

3) form all possible rate 1/2 and rate 1/3 Turbo Codes by combining each rate 1/2 constituent code pair with the test patterns;

4) evaluate a relative BER performance of all possible rate 1/2 and rate 1/3 Turbo Codes at a fixed Interleaver length;

5) select from the group of mother pairs, a subgroup of candidate pairs for building optimized Turbo Codes based upon a best overall BER performance;

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6) evaluate another relative BER performance of a Turbo Code group comprising the subgroup of candidate pairs punctured with the rate 1/2 and rate 1/3 puncturing patterns at a plurality of other Interleaver depths;

7) select from the Turbo Code group, a universal code pair which has another best overall relative BER for the Interleaver depths; and

8) encode data with a rate 1/2 or rate 1/3 Turbo Code comprising the selected universal code pair, at a first and a second encoder, the encoders similar and an Interleaver feeding bits into the second encoder, wherein the bits are ordered differently before entering each encoder.

Once generated, best Turbo Codes of lower rates such as 1/4, which are compatible with the rate 1/2 and 1/3 Turbo Codes determined by the above steps, can also be determined.

Rate 1/2 Constituent Codes

The following describes how rate 1/2 constituent codes are determined in one embodiment.

First, a list of candidate eight-state, rate 1/2 constituent code polynomials are determined.

Table 1 lists the determined denominator polynomials d(D) and numerator polynomials n(D) in octal notation. There are twelve constituent code candidates considered for initial screening purposes.

Table 1. Candidate 8-State Constituent Encoders of Rate 1/2

Denominator Polynomial d(D) (octal notation)	Numerator Polynomial n(D) (octal notation)
11	13
11	15
11	17
13	11
13	15
13	17
15	11
15	13
15	17
17	11
17	13
17	15

5

Each of the twelve (12) polynomials is expressed in octal form in Table 1, and has a corresponding binary and polynomial notation. The binary equivalent, for example of octal 13, is binary 1011.

10 Binary 1011 corresponds to a polynomial

$d(D) = D^0(1) + D^1(0) + D^2(1) + D^3(1) = 1 + D^2 + D^3$.

Next, the candidate Turbo Codes are simulated with an interleaver size of 1000 bits and three decoder iterations. The preliminary screening, which results are

15 shown in Figure 5 and Figure 6, evaluates the Bit Error Rate (BER) versus Ebi/No performance of all candidate Turbo Codes of rate 1/2 and rate 1/3, as described above. Measurement of Ebi/No is equivalent to a relative SNR.

The results of Figure 5 and Figure 6 are used

20 to select six (6) code polynomial pairs. The six (6) candidate universal code pairs, d(D)-n(D), are shown in octal representation on the left hand side of Table 2 below.

Next, a corresponding performance of the eight-

25 state Turbo Codes, using simulated data with the candidate universal codes at each rate and Interleaver depth, is used to construct Table 2. A sample

performance study or simulation is shown in Figures 7 and 8 showing selected Turbo Codes at an Interleaver depth of 512 bits for rate 1/2 and rate 1/3.

Table 2 below shows the approximate SNR loss for simulated data due to using a non-optimized code at rates 1/2 and 1/3 and Interleaver depths of 512, 1024, 2048, and 3072 bits.

Table 2. Approximate SNR Loss due to Use of Non-Optimized Codes

Candidate Universal Code: $d(D)$-$n(D)$	Turbo Code Rate & Frame Size (bits)							
	1/2 & 512	1/2 & 1024	1/2 & 2048	1/2 & 3072	1/3 & 512	1/3 & 1024	1/3 & 2048	1/3 & 3072
15-13	0.005 dB	0.00 dB	0.00 dB	0.05 dB	0.10 dB	0.05 dB	0.05 dB	0.10 dB
13-15	0.00	0.00 dB	0.00 dB	0.00 dB	0.05 dB	0.05 dB	0.05 dB	0.05 dB
15-17	0.05 dB	0.05 dB	0.00 dB	0.05 dB	0.05 dB	0.05 dB	0.00 dB	0.10 dB
17-15	0.40 dB	0.50 dB			0.00 dB	0.00 dB	0.05 dB	0.00 dB
17-13	0.40 dB	0.50 dB			0.00 dB	0.00 db	0.00 dB	0.00 dB
13-17	0.05 dB	0.05 dB	0.05 dB	0.00 dB	0.00 dB	0.10 dB	0.00 dB	0.10 dB

In a similar simulation using sixteen-state codes, pairs denoted as 31-33 and 31-27 are also shown in sample Figures 7 and 8 using four (4) decoder iterations for each sixteen-state code in order to provide similar complexity comparison with the eight-state codes using eight (8) decoder iterations. Eight-state codes with eight iterations out-perform sixteen state codes with four iterations significantly.

With separate simulations, the difference in performance amongst the different interleavers using the above six (6) candidate pairs is observed to be within 0.05 dB.

Finally, the results of Table 2 show that the following rate 1/2 constituent code pair provides the best overall performance across the ranges of rates and Interleaver sizes studied:

$$d(D)=1+D^2+D^3; \quad n(D)=1+D+D^3,$$

which represents octal 13 and octal 15, respectively.

In each tabulated case, the performance of Codes 13-15 is within 0.05 dB to the best performing code for that rate and Interleaver size.

This constituent code is thus selected as the basis for Turbo Code designs where higher code rates such as 1/2 and 1/3 are dominant.

Rate 1/3 Constituent Code

The following describes how rate 1/3 constituent codes are determined. Similar to the rate 1/2 constituent codes, rate 1/3 constituent code candidates are identified in Table 3 below for building near optimal Turbo Code rates of 1/4 and 1/5. For this case, the constituent code candidates for a Turbo Code must have three (3) polynomials instead of two (2).

Table 3. Candidate Constituent Codes for Optimized
Lower-Rate Turbo Codes

CC#1 (Octal 13-15/17)	CC#2 (Octal 15-13/17)	CC#3 (Octal 17-13/15)
$d(D)=1+D^2+D^3$ (Octal 13)	$d(D)=1+D+D^3$ (Octal 15)	$d(D)=1+D+D^2+D^3$ (Octal 17)
$n_1(D)=1+D+D^3$ (Octal 15)	$n_1(D)=1+D^2+D^3$ (Octal 13)	$n_1(D)=1+D^2+D^3$ (Octal 13)
$n_2(D)=1+D+D^2+D^3$ (Octal 17)	$n_2(D)=1+D+D^2+D^3$ (Octal 17)	$n_2(D)=1+D+D^3$ (Octal 15)

Optimal Rate 1/4 Turbo Codes

In order to build an overall rate 1/4 Turbo Code, various puncturing schemes must be considered in combination with each constituent codes of Table 3.

The various puncturing schemes of Figure 9 are first considered. For a rate 1/4 code, a common input information bit or systematic bit, is transmitted by one encoder, along with three (3) of four (4) parity bits produced for that input bit, by the two encoders.

The puncturing patterns of Figure 9, namely 910, 920, 930, and 940, are selected based upon the previously mentioned design principles, to meet stipulated code rates.

Next, each of the three (3) code triads of Table 3 is combined with the four (4) puncturing patterns 910, 920, 930 and 940, of Figure 9 to produce twelve (12) possible Turbo Codes to be evaluated with simulated data shown in Figures 10 through 12 for a fixed Interleaver depth of 512 bits, for example.

The performance of the twelve (12) Turbo Codes above is then used to select three (3) best Turbo Code candidates for a more detailed evaluation. Based on the simulation results shown in Figures 10 through 12, the three (3) best Turbo Code candidates from the twelve (12) are:

1) Turbo Code A - Constituent Code No. 1 with puncturing Pattern No. 2;

2) Turbo Code B - Constituent Code No. 2 with puncturing Pattern No. 1; and

3) Turbo Code C - Constituent Code No. 3 with puncturing Pattern No. 1. (Puncturing patterns are selected from Figure 9, Patterns 910, 920, 930 and 940).

One of the Turbo Codes of Codes A through C is next selected for further evaluation using simulated data at various additional Interleaver frame sizes to verify that the puncturing patterns are also good at other Interleaver depths.

To confirm the basic methodology, the performance of a Turbo Code based upon Constituent Code No. 1 (for example) is simulated for frame sizes of 1024, 2048 and 3072 bits. Sample results for BER/FER performance of Code #1 at 1024 bits is shown in Figure 13 and confirms the basic methodology.

Next, Figure 14 shows the BER/FER performance of simulated data using the three rate 1/4 Turbo Code Candidates A through C at an Interleaver depth of 512 bits. Consistent results are also achieved at Interleaver sizes 1024, 2048 and 3072 bits.

Next, a rate 1/4 Turbo Code candidate is selected from Candidate Turbo Codes A through C which provides the best overall performance at all Interleaver depths, in the simulation resulting in Figure 14 and analogous figures, such as those depicted in Appendix A. In the case of the rate 1/4 Turbo Code, optimization based on BER performance gives a different result than optimization based on FER performance. Turbo Code B has the best overall FER performance and Turbo Code C the best overall BER performance, for the simulated data. Figure 15 shows the performance of Turbo Code B as compared to other puncturing schemes.

Thus, FER optimized Turbo Code B is selected as the basis for the design since FER performance is usually the more important criteria for data services. On the other hand, Turbo Code A can be punctured to give the same universal Turbo Code identified previously as optimal for rate 1/3 (by puncturing all parity bits from the n_2 (D) polynomial). Hence, Turbo Code A is the preferred choice for the forward link rate 1/4 codes in order to have a single universal mother code to implement all of the different code rates.

Although current third generation CDMA encoding primarily concerns rate 1/4 channel encoding on the reverse link, rate 1/3 and rate 1/2 channel coding may be required for some of the highest rate data channels. A universal Turbo Code for rate 1/4, rate 1/3, and rate 1/2 can be designed, wherein the underlying constituent code is the same and only the puncturing pattern used is different. The method for generating the higher rate Turbo Codes from the rate 1/3 constituent code follows.

Rate 1/3 Turbo Codes Optimized at Rate 1/4

Using the constituent codes derived from the rate 1/4 optimized Turbo Codes above, namely Turbo Code B, the rate 1/3 and rate 1/2 Turbo Code can be designed to be compatible thereto. Thus, Constituent Code No. 2 (from Code B) is used as the basis.

Figure 16 shows seven (7) basic puncturing patterns that can be used to produce a rate 1/3 Turbo Code and four (4) basic puncturing patterns to produce a rate 1/2 Turbo Code. The seven (7) rate 1/3 patterns, 1602 through 1614 in block diagram 1600, show the consecutive information puncturing bit patterns, 1620, 1626, and the four (4) corresponding row parity bit puncturing patterns 1622, 1624, 1628, and 1630, for the two (2) encoder puncturing block patterns 1616 and 1618. As before, the pattern "1111" shown in row 1620 always transmits all the information bits from encoder 1. The pattern "0000" of row 1626, always punctures the information bits that enter by encoder No. 2. This is because it is not necessary to transmit the information bit twice. The four (4) rate 1/2 puncturing patterns, 1 through 4, identified in Figure 16 as element numbers 1640, 1642, 1644, and 1646, follow the same notation.

Next, in Figure 17 the BER and FER performance of all possible rate 1/3 Turbo Codes simulated with the preferred Constituent Code No. 2 at an Interleaver depth of 512 bits are compared.

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Then the two (2) best patterns are selected for further consideration. Next, the performance of these two (2) patterns are compared at further Interleaver depths 1024, 2048 and 3078 bits.

In Figure 17, for example, showing the rate 1/3 puncturing patterns at 512 bits, Patterns 2 and 5 are selected based upon curves 1710 and 1720, as having the best and next best overall relative FER, respectively.

Pattern 2 is then selected as the best performer over the various Interleaver depths from further simulations analogous to that of Figure 17 at additional Interleaver sizes for 1024, 2048 and 3072 bits.

Rate 1/2 Turbo Codes Optimized at Rate 1/4

Rate 1/2 Codes can also be optimized at lower rate codes for similar compatibility as described above. Figure 18 compares the BER and FER simulated performance of all the rate 1/2 Turbo Codes at an Interleaver depth of 512 bits. Figure 18 is generated using Constituent Code No. 2 and the four (4) puncturing patterns shown in Figure 16 for a rate 1/2 Turbo Code. Patterns 1 and 4 are determined to be the best based upon simulated curves 1810 and 1820 for FER performance.

As in the rate 1/3 case optimized at rate 1/4, similar simulation curves to Figure 18 are done for Patterns 1 and 4 for Interleaver depths of 1024, 2048 and 3072 bits. Based upon the resulting performance/curves Pattern 1 is judged to be the best pattern for FER performance.

Preferred Universal Turbo Codes Optimized for Rate 1/2 and 1/3

Figure 19 shows a block diagram for the constituent encoder optimized in accordance with the previously described method for Turbo Code rates 1/2 and 1/3. Figure 20 shows the block diagram for the corresponding Turbo Code punctured to rate 1/4.

Information bit stream X(t) 1902 is received at a

switch 1922, and is processed in accordance with several modular adders 1904, 1908, 1920, 1910, 1914, 1918, 1919, and several shift registers 1906, 1912 and 1916 which are hard-wired to represent two (2) numerator polynomials and one denominator polynomial.

In Figure 19, the denominator polynomial d(D), represented in octal 13, is hardwired by the return feedback connection to modular adders 1920 and 1904. Before computing, three shift registers 1906, 1912 and 1916 are first zeroed.

A first numerator polynomial over a denominator polynomial, represented by "1101", is hardwired to return output $Y_o(t)$ by combining: X(t) 1902 with a result of modulator adder 1920 to create a first bit W(t); the modular sum (second bit) of shift register 1906 and W(t) from the modular adder 1908; another zero bit (third bit) indicated by the lack of connection to the register 1912; and the modular sum (fourth bit) of another register 1916 and a result of modular adder 1908 from modular adder 1998. The result is $Y_o(t)=W(t)+S_o(t)+S_2(t)$.

In Figure 19 a second numerator polynomial over a denominator polynomial, represented by "1111", is hardwired to return output $Y_1(t)$ by combining: X(t) 1902 with a result of adder 1920 to create a first bit W(t); adding contents of a further register 1906 to W(t) with the contents of the modular adder 1910 (second bit); adding contents of the register 1912 a result of adder 1710 with the modular adder 1914 (third bit); and adding contents of the other register 1916 to a result of adder 1914 with modular adder 1919 (fourth bit). The result is $Y_1(t)=W(t)+S_o(t)+S_1(t)+S_2(t)$.

In Figure 19, the denominator polynomial connections sum the result of the register 1912 with register 1916 at adder 1920 and then adds it to X(t) 1902 at adder 1904. Thus, if modular adder 1904 is the value W(t), register 1906 holds $S_0(t)$, register 1912 holds $S_1(t)$ and register 1916 holds $S_2(t)$, and adder 1904 produces

$W(t)=X(t)+S_1(t)+S_2(t)$; $Y_0(t)=W(t)+S_0(t)+S_2(t)$; and $Y_1(t)=$ $W(t)+S_0(t)+S_1(t)+S_2(t)$. Thus, the adding is cumulative.

The result of a modular adder is a "1" if the two bits are different, and a "0" if the two bits are the same. Output $Y_o(t)$ represents the output from numerator Polynomial No. 1 and the denominator polynomial. Output $Y_1(t)$ represents numerator Polynomial No. 2 and denominator polynomial.

Initially, $S_0=S_1=S_2=0$ and the values of the registers 1906, 1912, 1916 are shifted from left to right after each clock cycle increment. Thus, $S_0(t+1)=W(t)$; $S_1(t+1)=S_0(t)$, and $S_2(t+1)=S_1(t)$.

The optimal puncturing matrices, shown in Figure 20, for example, show a "1" for transmitted bits and a "0" for punctured bits. Exemplary Figure 20 shows encoder 2000 with incoming bit X(t) and Interleaver 2002 passing interleaved bits X'(t) to encoder 2006 to produce output bit X'(t) and parity bits $Y_o^1(t)$, and $Y_1^1(t)$. None of the interleaved bits x'(t) are processed in the rate 1/4 encoder 2004, only in the second rate 1/4 encoder 2006. Block 2010 shows the puncturing pattern matrices.

More complicated puncturing patterns can be used to achieve other possible coding rates. For example, it is possible to select optimal puncturing patterns to achieve rates 3/8 and 4/9 for Turbo Codes optimized at rates 1/2 and 1/3; and to achieve rates 2/9 and 3/8 for Turbo Codes optimized at rate 1/4 using the preferred Turbo Codes identified in the invention.

Similar to Figure 9 the block diagram for an optimal Turbo Code rate 3/8 uses the rate 1/3 mother constituent code of Figure 20. The encoder for the constituent code of Figure 20 is shown in Figure 19. The puncturing pattern of the rate 3/8 Turbo Codes shown in Figure 21 punctures 1 out of every 6 bits associated with the first numerator polynomial from both encoders to generate a rate 3/8 Turbo Code.

The second pattern is a extension of the first pattern allowing both constituent encoders to have the

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same rate, namely 6/11. The extension pattern duplicates the same pattern (matrix) for another three (3) bits but moves the location of one transmission bit from one encoder to another, essentially flipping a "1" in one encoder while flipping a "0" in another encoder at the analogous locations.

Figure 22 shows the performance of these patterns at an Interleaver depth of 512 bits. Based on these and analogous curves at 1024, 2048, and 3072 Interleaver depths, Pattern 2 is chosen to implement the rate 3/8 Turbo Codes.

Figure 23 shows the puncturing patterns selected for rate 4/9 Turbo Codes used with the mother of codes of Figure 20. Similarly, the second pattern is an extension of the first, which allows both constituent encodes to have the same rate, namely 8/13.

Figure 24 shows the corresponding performance curves. Pattern 2 is chosen to implement the rate 4/9 Turbo Codes.

Thus, one exemplary Turbo Code design, optimized for Turbo Code rates 1/2 and 1/3, and universal for all Interleaver depths, has the preferred generator polynomials $d(D)=1+D^2+D^3$, n_1 $(D)=1+D+D^3$, and $n_2(D)=1+D+D^2+D^3$.

The preferred puncturing patterns for various code rates are:

1) Rate 1/4 - alternately puncturing parity bits n_1 from one encoder and n_2 from the same encoder;

2) Rate 1/3 - puncturing parity bits n_2 from both encoders;

3) Rate 1/2 - puncturing parity bits n_2 and alternately puncturing parity bits n_1 from both encoders;

4) Rate 3/8 - puncturing parity bits n_2 and one out of every 6 parity bits n_1 from both encoders; and

5) Rate 4/9 - puncture parity bits n_2 and uniformly 3 out of every 8 parity bits n_1 from both encoders.

A simplified version of this code is the universal Turbo Code design consisting of two constituent encoders having generator polynomials $d(D)=1+D^2+D^3$ and $n_1(D)=1+D+D^3$. (The third polynomial $n_2(D)$ is not used, so

5 the corresponding output is not generated and the encoder block diagram is simplified by removing the corresponding connections.) This universal Turbo Code design supports a minimum code rate equal to 1/3 (instead of 1/5). The corresponding preferred set of puncturing patterns are:

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1) Rate 1/3 - no puncturing
2) Rate 1/2 - alternately puncturing parity bits n_1 from both encoders;
3) Rate 3/8 - puncturing one out of every 6
15 parity bits n_1 from both encoders; and
4) Rate 4/9 - puncturing uniformly 3 out of every 8 parity bits n_1 from both encoders.

Preferred Universal Turbo Codes Optimized for Code Rate
20 **1/4**

The basic block diagram for a preferred constituent encoder is shown in Figure 25.

Figure 26 is an encoder block diagram for the preferred rate 1/4 Turbo Code. In this case, the second

25 parity bits are alternately punctured by the two constituent encoders. The preferred puncturing patterns described in earlier section can then be applied to produce rate 1/3 and rate 1/2 Turbo Codes. Other rates can also be supported by identifying further puncturing

30 patterns. This is illustrated by considering rates 2/9 and 3/8.

Figure 27 shows the puncturing patterns for a rate 2/9 Turbo Code. Three (3) different patterns are compared by performance curves in Figure 28 and analogous

35 curves, such as those set forth, for example, in Appendix A, showing performance at various frame Interleaver sizes. From a Pattern 2 FER curve 2810 and analogous curves, Pattern No. 2 is chosen as the optimal FER pattern for rate 2/9.

Next, Figure 29 illustrates six (6) initial screening puncturing patterns for optimizing a rate 3/8 Turbo Code. The performance of these patterns is simulated at a fixed Interleaver depth of 512 bits. Based on the simulation, Pattern 5 and Pattern 6 are chosen as the optimal puncturing patterns for further review.

Two more extension Patterns 7 and 8 of the above Patterns 5 and 6 duplicate the same patterns for another three information bits, but move the location of one of the transmission bits in the parity sequence from one encoder pattern to another. The extension allows both constituent encoders to have the same rate, namely 6/11 at each encoder.

Figure 30 shows exemplary performance curves of the above four (4) candidate puncturing Patterns 5, 6, 7 and 8 for rate 3/8 turbo Codes. Based on these results, a Pattern 8 FER curve 3010 and analogous curves such as those shown, for example, in Appendix A, demonstrate that Pattern 8 is the optimal puncturing pattern for rate 3/8 Turbo Codes.

Thus, one preferred Universal Turbo Code design optimized for Rate 1/4 uses two constituent codes having polynomials $d(D)=1+D+D^3$, $n_1=1+D^2+D^3$ and $n_2=1+D+D^2+D^3$.

The below puncturing patterns are associated optimized patterns as previously discussed for Turbo Code rate 1/4 and FER performance for most commonly used Turbo Code rates, where n_1 represents output bits associated with a first numerator polynomial, and n_2 represents output bits associated with a second numerator polynomial:

1) Rate 1/4 - alternately puncture parity bits n_2 from both constituent encoders.

2) Rate 1/3 - puncture parity bits n_1 from both constituent encoders;

3) Rate 1/2 - puncture parity bits n_2 and every other parity bits n_1 from both encoders;

4) Rate 2/9 - puncture every one out of every four parity bits in n_1 from both encoders; and

5) Rate 3/8 - puncture parity bits n_1 and one out of every six parity bits n_2.

These preferred puncturing patterns can also be cyclically shifted without affecting performance. The cyclically shifted patterns are equivalent.

Turbo Coding FEC Schemes for CDMA Data Services

The set of preferred universal Turbo Codes described heretofore in this invention provide a suite of flexible high performance channel codes that are well suited for sophisticated data communication systems requiring a variety of low speed and high speed data services. This suite of preferred universal Turbo Codes allows the crafting of different Turbo encoding schemes to meet the specific requirements of particular data communication systems.

As a first example, either of the following two FEC schemes is well-suited and recommended for a synchronous CDMA data communications network (such as the third generation CDMA 2000 system currently under development):

1) The preferred universal Turbo Code optimized at codes rates 1/2 and 1/3, along with a subset of associated preferred puncturing patterns, on a forward link; and the preferred universal Turbo Code optimized at code rate 1/4, along with a subset of the associated preferred puncturing patterns, on a reverse link; and

2) The preferred universal Turbo Code optimized at codes rates 1/2 and 1/3, along with a subset of associated preferred puncturing patterns, on both the forward and reverse links.

As a second example, either of the following FEC schemes is well-suited and recommended for an asynchronous CDMA data communications network (such as

the third generation CDMA systems currently in development in Europe and Asia):

    1) The preferred universal Turbo Code optimized at code rates 1/2 and 1/3, described above, along with a subset of associated puncturing patterns, on both the forward and reverse links;

    2) The preferred universal Turbo Code optimized at code rate 1/4, described above, along with a subset of the associated preferred puncturing patterns, on both the forward and reverse links; and

    3) The simplified version of the universal Turbo Code, described above, along with a subset of the associated preferred puncturing patterns, on both the forward and reverse links.

    The choice of which option to implement depends on the expected dominant code rate, minimum code rate, and implementation complexity constraints as well as other system requirements. Of course, additional puncturing patterns could be designed in accordance with the teachings of this invention to provide other Turbo Coding rates.

Other Variations

    The universal Turbo Codes identified for high-speed data services are especially suitable for third generation CDMA cellular mobile radio systems but could be easily applied to other systems as well.

    Well known variations such as Frame Oriented Convolutional Turbo Coding (FOCTC) could also be used in conjunction with the preferred universal constituent codes and universal Turbo Codes of this invention. The design methodology for selecting universal constituent codes and universal Turbo Codes can also be applied to alternate Turbo Code structures such as those involving more than two constituent encoders, and those involving serial concatenation instead of or in addition to parallel concatenation.

The exemplary preferred puncturing patterns described herein can be refined or modified in various ways by those skilled in the art. For example, a cyclic shift of a preferred puncturing pattern offers

5   substantially equivalent performance as the preferred puncturing pattern described herein. Furthermore, specific data communication systems may require different and additional puncturing patterns to support rate matching. These puncturing patterns may be designed in

10   accordance with the teachings of the present invention.

While the invention herein disclosed has been described by means of specific embodiments and applications thereof numerous modifications in variations could be made thereto by a skilled artisan and without

15   departing from the scope of the invention set forth in the claims.